Single-Mode ZBLAN Fiber Couplers

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Abstract. We demonstrate single-mode ZBLAN optical fiber couplers. A controlled tapering procedure leads to coupling ratios of 5%/95% and 14%/86% at a wavelength of 2200 nm, with insertion losses of 1.6 dB and 1.8 dB, respectively.

1 Introduction

Optical fiber couplers (OFCs) are components used for power dividing/combining, wavelength multiplexing/demultiplexing, filtering, and polarization beam splitting, broadly used in optical fiber devices and systems. Just like optical fibers, the vast majority of OFCs are made of silica glass. However, intrinsic losses prohibit the use of silica-based OFCs at wavelengths greater than $\sim 2\ \mu$m.

In contrast to silica, fluoride and chalcogenide fibers are transparent to mid-infrared light, up to 5 μm for ZBLAN and 12 μm for As_2Se_3 fibers. Chalcogenide OFCs have already been demonstrated in the form of single-mode OFCs [1–3], nonlinear OFCs [4], and also served in the fabrication of laser cavities [5, 6], but remain an emerging technology that needs refinement before commercialization. In contrast, fluoride glass OFCs have yet to be developed, mainly due to crystallization that spontaneously occurs close to the softening temperature [7]. Despite this major limitation and the competing development of chalcogenide-based OFCs, the realization of fluoride glass OFCs would lead to a complementary technology of strong interest because of their larger optical damage threshold and lower optical nonlinearity, compared to chalcogenide glass [8]. In 2016, G. Stevens et al. demonstrated the only fluoride glass OFC reported thus far [9]. The multi-mode ZBLAN OFC had a coupling ratio of up to 50%/50% at a wavelength of 2000 nm. The multimodedness of OFCs is however an impairment to the functionality of single-mode based optical fiber systems and devices. The fabrication of a single-mode OFC requires the use of single-mode fibers and the realization of appropriate adiabatic transition profiles on both sides of the OFC coupling section. The single-modedness of an OFC is validated from a smooth transmitted power versus OFC extension (during fabrication), as well as a smooth transmission spectrum, free from modal interference fluctuations [3].

Here, we demonstrate the successful fabrication of single-mode ZBLAN OFCs. The OFCs are fabricated using a multiple-sweep tapering technique that allows precise and repeatable control of the geometry. This results in single-mode OFCs with repeatable optical properties, while limiting crystallization. Complete transmission spectra of the OFCs over a $1500-2200$ nm band are provided, showing evidence of single-modedness. Coupling ratios following the OFC fabrication recipe can be varied anywhere from 0.1%/99.9% to 14%/86% at the through/cross ports, with a maximum insertion loss of 1.8 dB. This research is an important step towards the extension of optical fiber technologies in the mid-infrared.

2 Experiment and Results

To fabricate the OFCs, two pieces of ZBLAN fiber (Le Verre Fluoré) with core/cladding diameters of 6.5/125 μm and a numerical aperture of 0.23 are cleaved, polished, and coupled to SMF-28 using UV-cured epoxy. The two fibers are then placed together on a tapering setup with a twist of half a turn to ensure close contact of the fibers. Figure 1 shows a schematic of the tapering setup. Using an electrical heater, the fibers are heated at their softening temperature (290 °C) and stretched following an adiabatic tapering profile to avoid higher order modes excitation. This choice of temperature is a compromise between a colder temperature where viscosity becomes too large to enable stretching without breaking the fibers, and a higher temperature where crystallization grows too fast, leading to propagation losses before coupling can occur. During the tapering process, the heater brushes the waist of the OFC ~100 times with a velocity of 254 μm/s by moving back and forth in between the two pulling stages, resulting in a total tapering time of ~200 min. This allows the carving of a smooth transition region that adiabatically links the fiber mode to a tapered fiber mode, a uniform OFC waist region, and OFCs reproducibility. The tapering setup is enclosed in a box continuously purged with Argon gas to limit the crystallization process since ambient air acts as a catalyst.

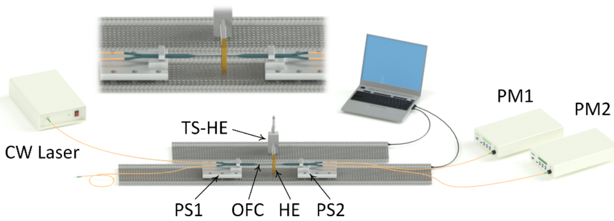

Figure 1. Schematic of the tapering setup. PS: pulling stage; HE: heating element; TS-HE: translation stage of the heating element; PM: power meter.

During tapering, continuous wave laser light is sent into one of the OFC's inputs and both though-port and cross-port outputs are monitored. Figure 2 shows the OFC

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transmission as a function of extension at a wavelength of 1550 nm, repeated for 3 OFCs with a waist length of 3 cm. Extension is the distance where the two pulling stages have moved away from each other since the beginning of the tapering process. At low extension, all the power remains in the through-port. However, as the tapering goes on with increasing extension, the fundamental modes guided by the two fiber cores increasingly overlap, leading to an increase in coupling. The tapering process is manually interrupted when the desired coupling ratio is achieved. The 3 OFCs demonstrate repeatable transmission patterns during the fabrication process. However, some OFCs break during the stretching. The rate of success in completing the extension of an OFC without breaking is of the order of 80%. Despite the actions taken to limit the crystallization, some crystallization is still triggered at the fiber surface and eventually gets deeper into the bulk material if tapering continues after a fiber diameter of ~30 μm. There is therefore a trade off in between tapering more to increase the coupling, and crystallization that eventually overlaps with the propagating light and increases losses.

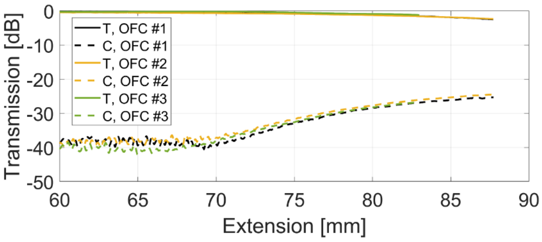

Figure 2. In situ transmission as a function of extension at the wavelength of 1550 nm, for 3 OFCs. T: through-port; C: cross-port.

Once the tapering process is completed, a broadband light source is launched into one input port of the OFC and the output power spectra from both arms are measured using an optical spectrum analyzer. Figure 3a shows the transmission spectra of OFC #3 made with a final waist fiber diameter of 27 μm and a waist length of 3 cm. The OFC has a larger coupling ratio at longer wavelengths due to a smaller V-number and weaker light confinement in both tapered fibers. The same reason is responsible for the larger insertion loss at longer wavelengths. More light interaction with the fiber surface leads to a larger scattering loss. OFC #3 provides a coupling ratio of 5%/95% with insertion losses of 1.6 dB at a wavelength of 2200 nm. To increase the coupling, the OFC waist length needs to be increased, and/or the fiber waist diameter needs to be decreased. Increasing the OFC waist length provides a longer interaction length for the light to couple to the second core. Decreasing the fiber waist diameter brings the two cores closer to each other, resulting in an increased modes overlap and larger coupling, but also more light interaction with the fiber-air interface where crystallization sets up and scattering loss occurs.

A fourth OFC is fabricated with the same fiber waist diameter but a longer waist length. Figure 3b shows the transmission spectra of OFC #4 with a waist fiber diameter of 27 μm and a waist length of 6 cm. Compared to OFC #3, OFC #4 has a larger coupling ratio. It shows a coupling ratio of 14%/86% with insertion losses of 1.8 dB at a wavelength of 2200 nm. The smooth transmission spectra of the OFCs and smooth transmission as a function of extension support the claim of single-modedness of the OFCs. Finally, ZBLAN OFCs are actually being kept at room temperature to observe their transmission as a function of time. For the time being, after two weeks of constant probing, no noticeable change could be detected on the OFC transmission. This measurement is still ongoing. In conclusion, we have demonstrated the first realization of single-mode couplers made of ZBLAN. This is an important step towards the extension of optical fiber technologies in the mid-infrared.

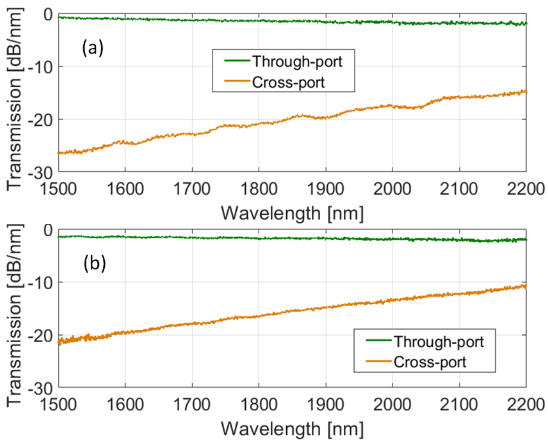

Figure 3. Transmission spectra of (a) OFC #3 with a waist length of 3 cm and (b) OFC #4 with a waist length of 6 cm.

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